Indian J. Phys. 77A (3), 255–260 (2003)

AN INTERNATIONAL JOURNAL
IJPA

Azimuthal angle dependence of two and three particle dynamical correlation among target fragments in ^{28}Si-AgBr interactions at 14.5 AGeV

Dipak Ghosh*, Argha Deb, Swarnapratim Bhattacharyya and Jayita Ghosh

Nuclear and Particle Physics Research Centre, Department of Physics, Jadavpur University, Kolkata-700 032, India

E-mail : dg@juphys.ernet.in

Received 14 August 2002, accepted 4 December 2002

Abstract : This paper reports an investigation on the two particle and three particle short range dynamical angular correlation in emission angle space among the target fragments produced in ^{28}Si-AgBr interactions at 14.5 AGeV on different range of azimuthal angles $0° \leq \phi \leq 90°$, $90° \leq \phi \leq 180°$, $180° \leq \phi \leq 270°$ and $270° \leq \phi \leq 360°$. The experimental data have been compared with the Monte Carlo simulated events to extract dynamical correlation. The analysis reveals that both two and three particle dynamical correlation among target fragments depend on the azimuthal angle space.

Keywords : Target fragmentation, correlation, azimuthal angle dependence.

PACS Nos. : 25.75.-q, 25.70 Mn

Introduction

Investigation of correlation effect in terms of two and many particle correlation function is one of the most popular trends in high energy physics because the study of correlation can encapsulate rich information about the space time structure and the dynamics of the emitting source in the late stage of reaction where the nuclear matter is highly excited and diffused [1–3]. Several studies using well known two and three particle short range correlation function have been reported in different type of interactions [4–19]. It was observed that in all types of nuclear interactions stated above [4–19], the produced particles showed a tendency to be emitted in a correlated fashion. The reason behind this may be the formation of exotic nuclear matter, hot multi-nuclear fire ball or formation of heavier intermediate states, clusterisation *etc*. Therefore, a detailed correlation study is essential to search for the exact reason of correlated emission of particles speculated by different theorists.

It is to mention that during the previous investigations, emphasis has been given on pions [20] as the pions are most frequently produced particles in high energy collisions and the knowledge of pion production mechanism is essential for understanding the main features of high energy multi-particle production. On the contrary, very little attention is paid on the target evaporated slow particles. They are emitted at the late stage of nuclear reaction and so they are expected to remember the parts of the history of interactions. So the study of this target evaporated particles is of great importance and a potential source of information can also be had from a detailed analysis on target fragments. This less explored area should be probed with all available tools.

In this article, we deal with the target fragments from nuclear interactions. The nuclear fragmentation or evaporation data are very conveniently provided by nuclear emulsion experiments. The characteristics of target evaporated low energy particles are not revealed as yet in detail.

*Corresponding Author

"Target evaporated particles are identified as the black tracks in a model referred to as the evaporation model" [21]. According to this model, 'shower' and 'grey' tracks are emitted from the nucleus very soon after the instant of impact. This leaves the nucleus in a highly excited state. Indeed, the excitation energy may sometimes be comparable with the total binding energy of the nucleus. Emission of heavily charged particles from this state, however, now takes place relatively slowly. In order to escape from the residual nucleus, a particle must await a favourable statistical fluctuation arising out of random collisions among the nucleons. Emission occurs if due to a fluctuation, it is close to the nuclear boundary, travlling in an outward direction; and has kinetic energy greater than its binding energy. After the evaporation of this particle, a further relatively long period on a nuclear time scale, say 10^{-17} sec, will commonly elapse before a second particle is also placed in conditions favorable for escape and so on. The process continues until the excitation energy of the residual nucleus is so small that transition to the ground state is likely to be affected by the emission of the gamma rays. In the rest system of the nucleus in this model, the direction of emission of the evaporation particles is distributed isotropically. The evaporation model is based on the assumption that statistical equilibrium has been established in the decaying system and lifetime is much longer than the time taken to distribute the energy among the nucleons within the nucleus. Evaporation model predicts an isotropic emission of target fragments in the laboratory system. But the isotropic emission of target fragments is not supported by different works [22–24]. So in order to have a deep insight in to the dynamics of nuclear fragmentation, the study of two and three particle correlation needs a thorough exploration.

In a very recent study, we have reported [25] strong two and three particle dynamical correlation among target fragments produced in ^{28}Si-AgBr interactions at 14.5 AGeV.

In this paper, we study the azimuthal angle dependence of two and three particle dynamical correlation in ^{28}Si-AgBr interactions at 14.5 AGeV.

2. Experimental method

The data were obtained from Illford G5 emulsion stacks exposed horizontally to ^{28}Si beam of energy 14.5 AGeV from Alternating Gradient Synchrotron at Brookhaven National Laboratory (BNL AGS) [26]. A Leitz Metaloplan microscope with a 10X objective and 10X ocular lens provided with a semi-automatic scanning stage was used to scan the plates. Each plate was scanned by two independent observers to increase the scanning efficiency. The final measurements were done using an oil-immersion 100X objective. The measuring system fitted with it has 1 μm resolution along the X and Y axes and 0.5 μm resolution along the Z axis.

After scanning, the events were chosen according to the following criteria :

(i) The incident beam track should not lie more than 3° from the main beam direction in the pellicle. It is done to ensure that we have taken the real projectile beam.

(ii) Events showing interactions within 20 μm from the top or bottom surface of the pellicle were rejected. It is done to reduce the loss of tracks as well as to reduce the error in angle measurement.

(iii) The tracks of the incident particle, which induce interactions, were followed in the backward direction to ensure that it is a projectile beam starting from the beginning of the pellicle.

According to the emulsion terminology [21] the particles emitted after interactions are classified as :

A. Black particles :

Black particles consist of both single and multiple charged fragments. They are target fragments of various elements like carbon, lithium, beryllium *etc.* with ionization greater or equal to 10 I_0, I_0 being the minimum ionization of a singly charged particle. The range of black particles in the emulsion medium is less than 3 mm. They have velocities less than 0.3 c. Energies of these particles are generally less than 30 MeV. c is the velocity of light in vacuum. In the emulsion experiments, it is very difficult to measure the charges of the fragments. So identification of the exact nucleus is not possible.

B. Grey particles :

They are mainly fast target recoil protons with energy upto 400 MeV. Ionisation power of grey particles lies between 1.4 I_0 to 10 I_0. Their ranges are greater than 3 mm. These grey particles have velocities lying between 0.3 c to 0.7 c

C. Shower particles :

The shower tracks with ionization I less than or equal to 1.4 I_0 are mainly produced by relativistic pions and are not generally confined within the emulsion pellicle. These shower particles have energy in GeV range.

D. The projectile fragments :

They are a different class of tracks with constant ionization, long range and small emission angle.

To ensure that the targets in the emulsion are silver or bromine nuclei, we have chosen only the events with at least eight heavy ionizing tracks of (black + grey) particles. The events that have the number of heavy tracks less than eight are due to the collision of the projectile beam with carbon, nitrogen and oxygen nucleus present in the emulsion. These types of events are called CNO events.

According to the above selection procedure, we have chosen 350 events of ^{28}Si-AgBr interactions at 14.5 AGeV. The emission angle (θ) and azimuthal angle (ϕ) with respect to the beam direction were measured for each track by taking the coordinates of the interaction point (X_0, Y_0, Z_0), coordinates (X_1, Y_1, Z_1) at the end of the linear portion each secondary track and coordinate (X_i, Y_i, Z_i) of a point on the incident beam. During the calculation of the emission angle and azimuthal angle using coordinate geometry, the coordinate normal to the emulsion plate (along the Z axis) is corrected for the shrinkage of emulsion during processing. Nuclear emulsion covers 4π geometry and provides very good accuracy in the angle measurements of produced particles and fragments due to high spatial resolution and thus is suitable as a detector for the study of fluctuations in the fine resolution interval of considered phase space.

3. Method of analysis

Two particle correlation :

For phase space variable z, two particle normalised correlation function is defined as

$$R(z_1,z_2) = \frac{\rho_2(z_1,z_2)-\rho_1(z_1)\rho_1(z_2)}{\rho_1(z_1)\rho_1(z_2)}$$

$$= \frac{\rho_2(z_1,z_2)}{\rho_1(z_1)\rho_1(z_2)} - 1,$$

where the quantities $\rho_1(z) = \frac{1}{\sigma}\frac{d\sigma}{dz}$; $\rho_2(z_1,z_2) = \frac{1}{\sigma}\frac{d^2\sigma}{dz_1dz_2}$ represent one- and two-particle densities respectively. R can be represented as

$$R(z_1,z_2) = N_T\frac{N_2(z_1,z_2)}{N_1(z_1)N_1(z_2)} - 1,$$

where N_T is the total number of inelastic events. $N_1(z_1)$ is the number of balck tracks at the phase space z_1 and $z_1 + dz_1$. $N_1(z_2)$ is the number of black tracks at the phase space z_2 and $z_2 + dz_2$, $N_2(z_1,z_2)$ is the number of pairs of particles having one particle between the phase space z_1 and $z_1 + dz_1$ and the other particle between z_2 and $z_2 + dz_2$ in an event.

For the present work, R in terms of $\cos\theta$ is represented

$$R(\cos\theta_1,\cos\theta_2) = N_T\frac{N_2(\cos\theta_1,\cos\theta_2)}{N_1(\cos\theta_1)N_1(\cos\theta_2)} - 1 \qquad (1)$$

The idea of using correlation function of the above forms goes to the work of Krikwood [27] in statistical physics. $R = 0$ implies absence of correlation *i.e.* the case of completely independent particle emission.

Three particle correlation :

Three particle inclusive correlation function for phase space variable z can be defined as [28] :

$$R(z_1,z_2,z_3) = \frac{\rho_3(z_1,z_2,z_3)+2\rho_1(z_1)\rho_1(z_2)\rho_1(z_3)}{\rho_1(z_1)\rho_1(z_2)\rho_1(z_3)}$$

$$\frac{\rho_2(z_1,z_2)\rho_1(z_3)+\rho_2(z_2,z_3)\rho_1(z_1)+\rho_2(z_3,z_1)\rho_1(z_2)}{\rho_1(z_1)\rho_1(z_2)\rho_1(z_3)},$$

where the quantity $\rho_3(z_1,z_2,z_3) = \frac{1}{\sigma}\frac{d^2\sigma}{dz_1dz_2dz_3}$ represents three particle density. ρ_1 and ρ_2 represent the same quantities as in case of two particle correlation.

In terms of the number of particles, R can be represented as

$$\begin{aligned}R(z_1,z_2,z_3) &= N_T^2N_3(z_1,z_2,z_3)/[N_1(z_1)N_1(z_2)N_1(z_3)]\\ &-N_TN_2(z_1,z_2)/[N_1(z_1)N_1(z_2)]\\ &-N_TN_2(z_2,z_3)/[N_1(z_2)N_1(z_3)]\\ &-N_TN_2(z_3,z_1)/[N_1(z_3)N_1(z_1)]+2,\end{aligned}$$

where $N_3(z_1, z_2, z_3)$ is the number of triplets of particles having one particle between the interval z_1 to $z_1 + dz_1$ other particle between z_2 to $z_2 + dz_2$ and the third particle between z_3 to $z_3 + dz_3$ in an event.

For our case,

$$\begin{aligned}&R(\cos\theta_1,\cos\theta_2,\cos\theta_3)\\ &= N_T^2N_3(\cos\theta_1,\cos\theta_2,\cos\theta_3)/\\ &[N_1(\cos\theta_1)N_1(\cos\theta_2)N_1(\cos\theta_3)]\\ &-N_TN_2(\cos\theta_1,\cos\theta_2)/[N_1(\cos\theta_1)N_1(\cos\theta_2)]\\ &-N_TN_2(\cos\theta_2,\cos\theta_3)/[N_1(\cos\theta_2)N_1(\cos\theta_3)]\\ &-N_TN_2(\cos\theta_3,\cos\theta_1)/[N_1(\cos\theta_3)N_1(\cos\theta_1)]+2. \quad (2)\end{aligned}$$

4. Monte Carlo simulation

Correlation among the target fragments may arise due to the reasons given below, apart from the presence of any true dynamics behind this.

(i) Board multiplicity distribution.

(ii) The dependence of single particle spectrum $\frac{1}{\sigma}\frac{d\sigma}{dz}$ on the multiplicity.

(iii) The trivial statistical fluctuations.

To search for the non-trivial dynamical correlation among the target-associated slow particles, the experimental data have to be compared with those calculated from Monte Carlo simulation.

We have utilized the framework of independent emission hypothesis for simulation using the following assumptions :

(i) The target fragments are emitted independently.

(ii) The multiplicity distribution of the Monte Carlo events in the same as the empirical multiplicity spectrum of the real ensemble.

(iii) The single particle spectrum $\frac{1}{\sigma}\frac{d\sigma}{dz}$ of the simulated events reproduces the distribution $\frac{1}{\sigma}\frac{d\sigma}{dz}$ of the experimental data.

The difference between the experimental values and Monte Carlo values can be interpreted as the dynamical surplus which arises due to some dynamics in the reaction process. The dynamical surplus can be written as

$$R_D = R - R_M, \tag{3}$$

where R is the experimental values and R_M is the value obtained from Monte Carlo simulation.

5. Results and discussion

Two particle correlation :

To analyse the azimuthal angle dependence of two and three particle correlation, we first divide the total azimuthal phase space into four equal divisions : $0° \le \phi \le 90°$, $90° \le \phi \le 180°$, $180° \le \phi \le 270°$ and $270° \le \phi \le 360°$. The two particle normalized correlation function R is calculated with the help of eq. (1). Figure 1 shows the plots of two particle

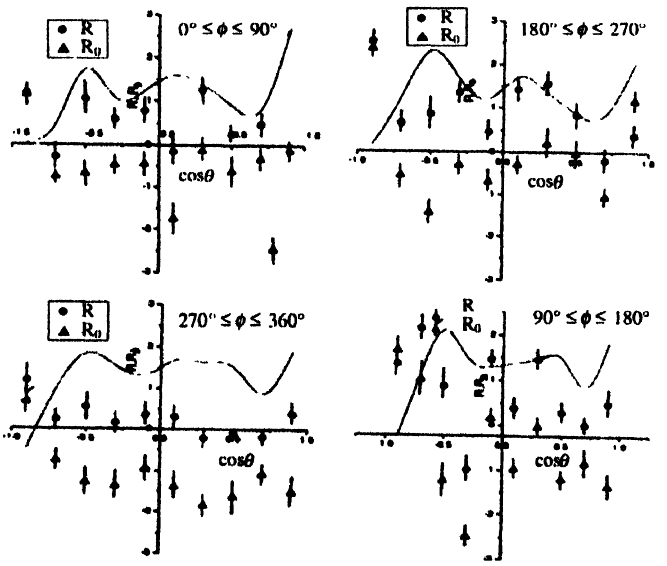

Figure 1. Represents the plot of correlation function R against $\cos\theta$ and dynamical surplus value R_D against $\cos\theta$ in case of two particle correlation for $\phi = 0° \le \phi \le 90°$, $90° \le \phi \le 180°$, $180° \le \phi \le 270°$ and $270° \le \phi \le 360°$.

normalized correlation function R against $\cos\theta$ in different azimuthal zones ($0° \le \phi \le 90°$, $90° \le \phi \le 180°$, $180° \le \phi \le 270°$ and $270° \le \phi \le 360°$) for the diagonal elements ($\cos\theta_1 = \cos\theta_2 = \cos\theta$) of the correlation matrices characterising the magnitude of the short range correlation at different phase space intervals. The dots in the figure represent the experimental values and the thick curve represents the values of the correlation function as calculated from Monte Carlo simulation. The dynamical surplus correlation R_D in the four sub divisions stated above are also plotted in the same figure. It is evident from the figure that the dynamical surplus values are non-zero for all values of $\cos\theta$ which implies that short range two particle dynamical correlation exists in every azimuthal zones.

From the figure, it is seen that in the region $0° \le \phi \le 90°$ correlation is most prominent at $\cos\theta = 0.9$. Appreciable correlation effect is also observed at $\cos\theta = 0.1$ and $\cos\theta = -0.9$.

If we consider the region $90° \le \phi \le 180°$ we find the most prominent correlation occurs at $\cos\theta = -0.3$. However signature of stronger correlation is also present $\cos\theta = -0.9$ and $\cos\theta = 0.9$.

In the interval $180° \le \phi \le 270°$, at $\cos\theta = -0.9$ the dynamical correlation is most prominent. Strong signal of dynamical correlation can be noticed at $\cos\theta = 0.9$ and $\cos\theta = -0.5$.

In the fourth interval, correlation is most prominent at $\cos\theta = 0.3$. However from $\cos\theta = 0.1$ to $\cos\theta = -0.9$, noticeable correlation is present. It is also revealed from the graphs that for all the azimuthal zones, weaker correlation is present at $\cos\theta = -0.7$ and -0.1.

Three particle correlation :

The three-particle normalised correlation function is calculated for different values of $\cos\theta$ with the help of eq (2). Short range correlation is investigated by plotting the values of the diagonal elements of the correlation matrices ($\cos\theta_1 = \cos\theta_2 = \cos\theta_3 = \cos\theta$) against $\cos\theta$ variable The thick cruves in the figure represent the values of correlation function calculated by Monte Carlo simulation and the dots represent the experimental values. Figure 2 shows the plot of three particle normalized correlation function R against $\cos\theta$ in the azimuthal intervals $0° \le \phi \le 90°$, $90° \le \phi \le 180°$, $180° \le \phi \le 270°$ and $270° \le \phi \le 360°$.

The dynamical surplus correlation R_D in the four sub-divisions stated above, are also plotted in the same figure. From the non-zero values of dynamical surplus, it can be said that for all values of $\cos\theta$, short range three particle dynamical correlation exists.

In case of three particle correlation when ϕ lies between 0° and 90°, most prominent correlation occurs at $\cos\theta = 0.9$. However, strong correlation is also present at $\cos\theta = 0.1$.

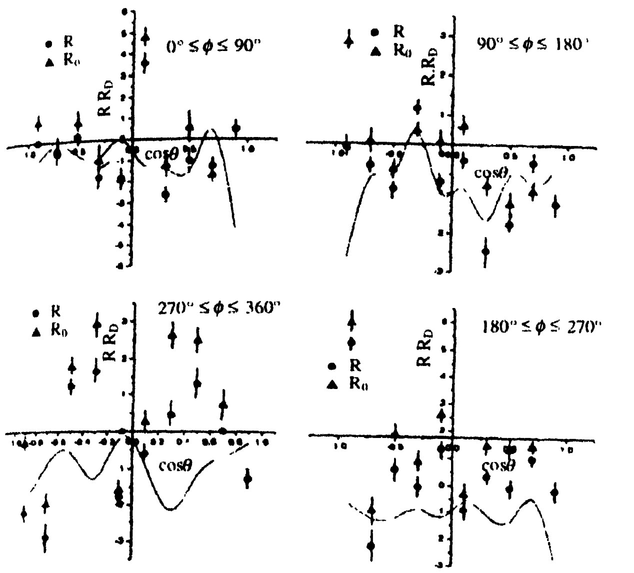

Figure 2. Represents the plot of correlation function R against $\cos\theta$ and dynamical surplus value R_D against $\cos\theta$ in case of three particle correlation for ϕ = 0° ≤ ϕ ≤ 90°, 90° ≤ ϕ ≤ 180°, 180° ≤ ϕ ≤ 270° and 270° ≤ ϕ ≤ 360°.

Considering the interval 90° ≤ ϕ ≤ 180°, we see that at $\cos\theta = -0.9$, correlation effect is most prominent. In other values of $\cos\theta$ excepting $\cos\theta = 0.5$, correlation effect is much weaker. If we turn our attention to the division 180° ≤ ϕ ≤ 270°, we find that maximum correlation occurs at backward hemisphere ($\cos\theta = -0.9$). However in the forward hemisphere, noticeable correlation effect is observed for $\cos\theta = 0.3-0.9$. So here correlation is occurring in both forward and backward hemispheres.

In the interval 270° ≤ ϕ ≤ 360°, correlation is most prominent at $\cos\theta = -0.3$. Prominent correlations are also present at $\cos\theta = 0.3$ and $\cos\theta = 0.5$. So here also correlation is occurring in both forward and backward hemispheres.

Hence, we can say that both two particle and three particle correlations exist in the four different spaces. However in some regions of ϕ-space, correlation is strongest in both forward and backward hemispheres and in some regions it is either strongest in forward hemisphere or in backward hemisphere. It can also be concluded that most prominent correlation does not occur for same value of $\cos\theta$ in all the ϕ intervals. Comparing the figures showing the variation of R_D against $\cos\theta$ for the four ϕ regions, we can conclude that two and three particle correlation functions depend not only on $\cos\theta$ but also strongly on ϕ-space. Earlier we have investigated [25] two and three particle correlations in the emission angle-space in target fragmentation of ^{28}Si-AgBr interactions at 14.5 AGeV. That analysis yields that minimum two particle correlation occurs at $\cos\theta = 0.9$ and minimum three particle correlation occurs at $\cos\theta = -0.1$. Study of azimuthal angle dependence of two and three particle correlation indicates that appreciable amount of correlation is present for those two $\cos\theta$ values in all azimuthal angular zones. So study of correlation considering the total ϕ-space lacks some information on true signal of dynamical correlation. Full information on dynamical correlation can only be obtained considering each ϕ zones. Theoretical models on correlations should be made considering this azimuthal angle effect on correlation.

This analysis provides new information on two particle and three particle correlation which is not only interesting but also extremely useful for understanding the emission of target fragments in high energy nucleus-nucleus interactions.

Acknowledgment

The authors are grateful to Prof. P L Jain, State University of Buffalo, Buffalo, U.S.A., for providing us with the exposed and developed emulsion plates used for this analysis. We also like to acknowledge the financial help sanctioned by the University Grants Commission (Govt. of India) under their COSIST programme.

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